

Cryptanalysis of KLEIN

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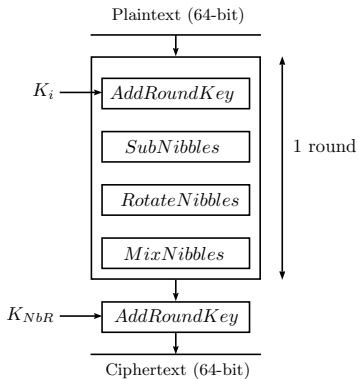
March 27th 2014



- 1 The KLEIN Block Cipher
- 2 Previous Analyses
- 3 Some Properties
- 4 New Attack
- 5 Results

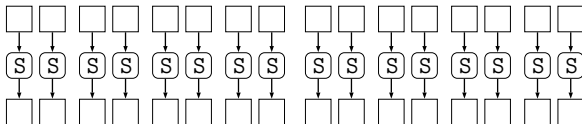
The KLEIN Block Cipher

Family of Lightweight Block Ciphers presented at RFIDSec 2011
by Zheng Gong, Svetla Nikova, and Yee Wei Law



Version	Key Size	Rounds
KLEIN-64	64	12
KLEIN-80	80	16
KLEIN-96	96	20

SubNibbles (SN)



Splits the state into 4-bit parts (nibbles) and applies the following Sbox:

x	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
S[x]	7	4	a	9	1	f	b	0	c	3	2	6	8	e	d	5

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CipherRound Function
Key-Schedule

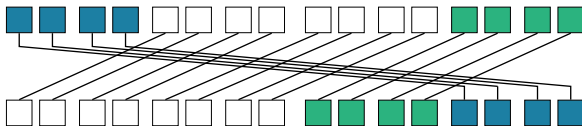
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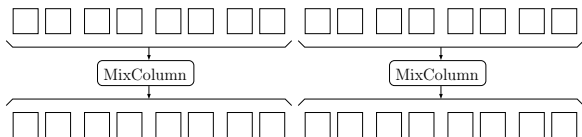
RotateNibbles (RN)



Cyclic rotation of the state leftwards by 2 bytes / 4 nibbles.

MixNibbles (MN)

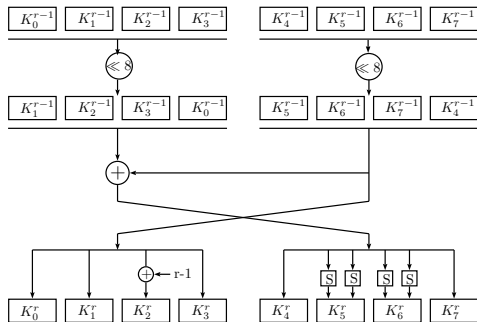
Byte wise operation computing AES MixColumn transformation on each half of the state



A byte is seen as an element of $GF(2^8) = GF(2)/x^8 + x^4 + x^3 + x + 1$
The output is composed of 4 bytes resulting from multiplication with the following matrix:

$$\begin{pmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{pmatrix}$$

Key-Schedule (KLEIN-64)



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Main Idea of Previous Analyses

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proposition [ANS 11][YWLZ 11]

During encryption and key derivation, there is a slow diffusion between higher and lower nibbles.

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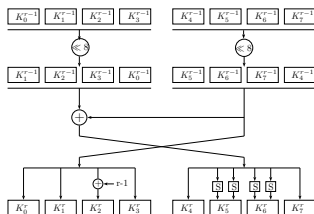
During encryption and key derivation, there is a slow diffusion between higher and lower nibbles.

Version	Attacks	Rounds	Data	Time	Memory	Source
KLEIN-64	integral	7	$2^{34.3}$	$2^{45.5}$	2^{32}	[YWLZ 11]
	truncated	8	2^{32}	$2^{46.8}$	2^{16}	[YWLZ 11]
	differential	8	2^{35}	2^{35}	-	[ANS 11]
	PC MITM	10	1	2^{62}	2^{60}	[NWW 13]
	biclique	12	2^{39}	$2^{62.84}$	$2^{4.5}$	[ASR 13]
KLEIN-80	integral	8	$2^{34.3}$	$2^{77.5}$	2^{32}	[YWLZ 11]
	PC MITM	11	2	2^{74}	2^{74}	[NWW 13]
	biclique	16	2^{48}	2^{79}	2^{60}	[AFLLW 12]
KLEIN-96	PC MITM	13	2	2^{94}	2^{82}	[NWW 13]
	biclique	20	2^{32}	$2^{95.18}$	2^{60}	[AFLLW 12]

Properties

proposition [ANS 11][YWLZ 11]

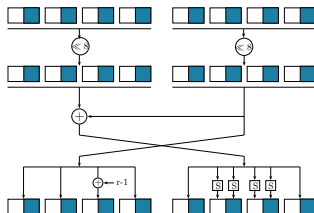
In the KeySchedule algorithm, **lower nibbles and higher nibbles are not mixed**: the lower nibbles (resp. higher nibbles) of any round-key can be computed directly from the lower nibbles (resp. higher nibbles) of the master key.



Properties

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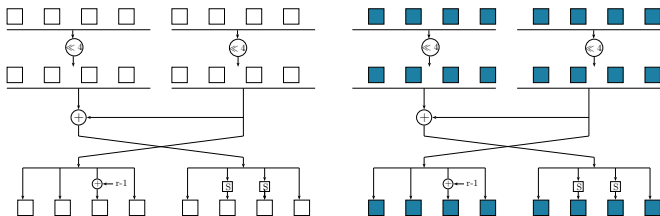
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proposition [ANS 11][YWLZ 11]

All layers except `MixNibbles` are nibble-wise and do not mix higher nibbles with lower nibbles.

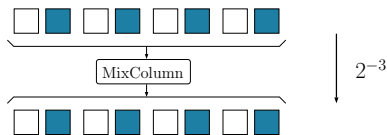
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proposition [ANS 11][YWLZ 11]

All layers except MixNibbles are nibble-wise and do not mix higher nibbles with lower nibbles.

proposition [ANS 11][YWLZ 11]

If the state entering MixColumn has **inactive higher nibbles**, then the output has the same pattern if and only if the MSB of the 4 lower nibble differences all have the same value. This case occurs with **probability 2^{-3}** . The same property holds for MixColumn^{-1}



Resulting Truncated Differential Attack [ANS 11]

Plaintext																				
1	SN	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	RN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	MN	□	■	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□
2	SN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	RN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	MN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
3	SN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	RN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	MN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
4	SN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	RN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	MN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
5	SN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	RN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	MN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
6	SN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	RN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	MN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
7	SN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	RN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	MN	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	Ciphertext	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

 $2^{-0.42}$

- Probability $2^{-28.82}$

 $2^{-4.40}$

- Find several conforming pairs

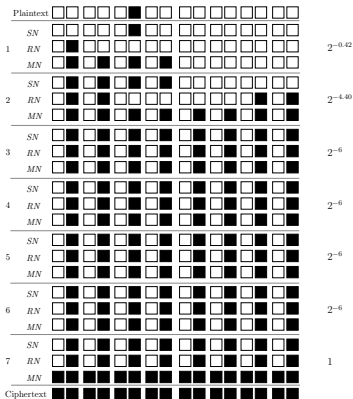
 2^{-6}

- Use the difference before MN at round 6 to reduce the key space (2^{-6})

 2^{-6} 2^{-6} 2^{-6}

1

Resulting Truncated Differential Attack [ANS 11]

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- Find several conforming pairs

 2^{-6}

- Use the difference before MN at round 6 to reduce the key space (2^{-6})

 2^{-6}

If we try to attack more rounds:

 2^{-6}

- Hard to filter conforming pairs

 2^{-6}

- Expensive to get several ones

1

Cryptanalysis of
KLEIN

Lallemand and
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New Attack

The KLEIN Block
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Access MN of the previous rounds to obtain bigger sieves

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Access MN of the previous rounds to obtain bigger sieves

- Build triples made up of 2 messages and a possible value for the lower nibbles of the master key
- Test together if the key guess is correct and if the pair is conforming to the differential path
- Invert a round to access another MN step and use the associated filter to discard triples

How to Invert a Round:

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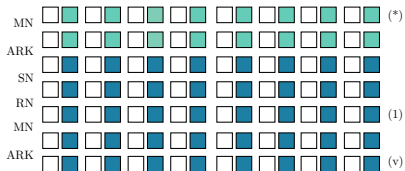
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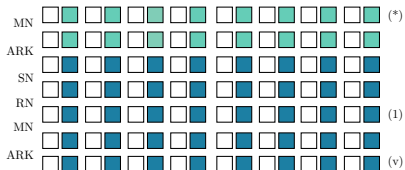
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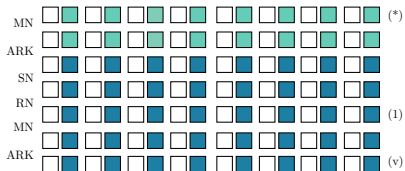
How to Invert a Round:



Given: Candidate triple that has passed the test at point (1)
Associated values of the state lower nibbles at point (v)

Goal: Compute the difference at point (*):

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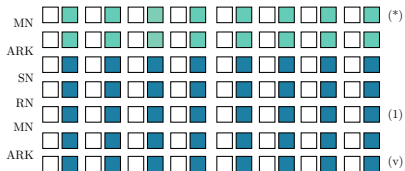


Given: Candidate triple that has passed the test at point (1)
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- Invert SN (value)

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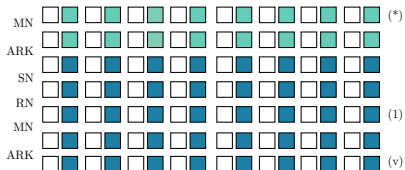


Given: Candidate triple that has passed the test at point (1)
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- Invert RN

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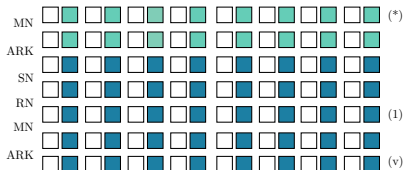


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- Invert ARK (Key Schedule property)

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Goal: Compute the difference at point (*):

- Invert SN (value)
- Invert RN
- Invert ARK (Key Schedule property)
- We have to invert MN in lower nibbles

Inverting a Round: MN case

Let $(a_0, a_1, a_2, a_3, a_4, a_5, a_6, a_7)$ be the binary decomposition of a byte a .

(a_0, a_1, a_2, a_3) the higher nibble

(a_4, a_5, a_6, a_7) the lower nibble

proposition

To compute the lower nibbles of the input of *MixColumn* given the lower nibbles of the output (a, b, c, d) , we require 3 information bits from the higher nibbles:

$$\begin{cases} a_1 + a_2 + b_2 + c_0 + c_1 + c_2 + d_0 + d_2 \\ a_1 + b_0 + b_1 + c_1 + d_0 + d_1 \\ a_0 + a_1 + a_2 + b_0 + b_2 + c_1 + c_2 + d_2 \end{cases}$$

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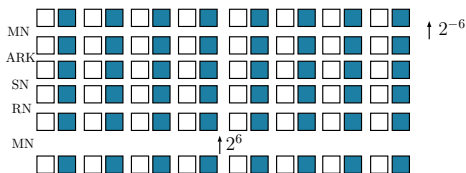
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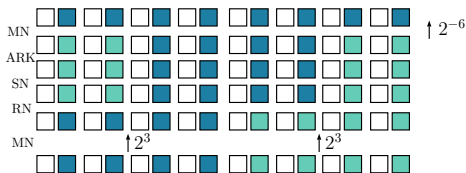
⇒ a 6-bit guess suffices to predict the lower nibbles entering MixNibble

Inverting a Round: MN case



- We invert MN for the 2^6 possibilities for the 6-bit guesses
- The conditions on the previous MN give us a filter of 2^{-6}

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- We can invert independently the 2 MC to reduce the cost of this operation (2^4 round computations instead of 2^6)

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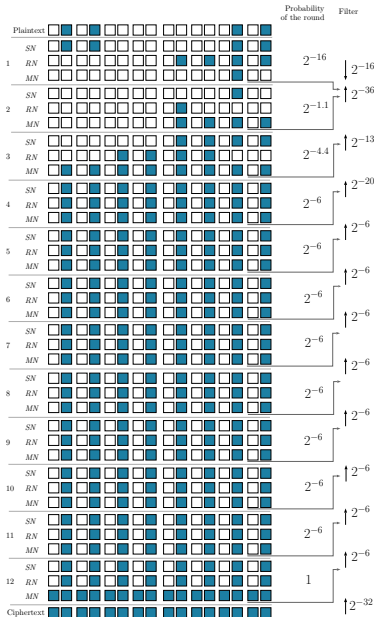
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Path of probability $2^{-69.5}$

For each pair with higher nibbles inactive before the last MN :

- 1 Guess the Lower Nibbles of the key and use the first round as a filter
- 2 Invert the last round with a 6-bit guess
- 3 Use the difference obtained before MN as a filter
- 4 Invert another round
- 5 The first rounds give us more efficient filters
- 6 Finally we compare the values of the lower nibbles recovered with the value of the plaintext

Results

- At the end, $2^{8.5}$ triples remain
- Higher Nibbles search discards the incorrect values

Source	Rounds	Data	Time	Memory	Attacks
[YWLZ 11]	7	$2^{34.3}$	$2^{45.5}$	2^{32}	integral
[YWLZ 11]	8	2^{32}	$2^{46.8}$	2^{16}	truncated
[ANS 11]	8	2^{35}	2^{35}	-	differential
[NWW 13]	10	1	2^{62}	2^{60}	PC MITM
[ASR 13]	12	2^{39}	$2^{62.84}$	$2^{4.5}$	biclique
Our New Attack	12	$2^{54.5}$	$2^{57.07}$	2^{16}	truncated

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Conclusion

- First attack on the full version of KLEIN-64
- Verified experimentally on round-reduced versions (first practical attacks on 10 rounds)
- Reaches 13 rounds out of 16 of KLEIN-80
- 14 rounds out of 20 of KLEIN-96
- Changing the MDS matrix in MixNibble or the KeySchedule might counter these attacks

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Thank you for your attention